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FATIGUE IN SINGLE CRYSTAL NICKEL SUPERALLOYS
Technical Progress Report

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I. Introduction and Program Objective

This program investigates the seemingly unusual behavior of single crystal airfoil materials. The fatigue initiation processes in single crystal (SC) materials are significantly more complicated and involved than fatigue initiation and subsequent behavior of a (single) macrocrack in conventional, isotropic, materials. To understand these differences it is helpful to review the evolution of high temperature airfoils.

Characteristics of Single Crystal Materials

Modern gas turbine flight propulsion systems employ single crystal materials for turbine airfoil applications because of their superior performance in resisting creep, oxidation, and thermal mechanical fatigue (TMF). These properties have been achieved by composition and alloying, of course, but also by appropriate crystal orientation and associated anisotropy.

Early aeroengine turbine blade and vane materials were conventionally cast, equiaxed alloys, such as IN100 and Rene'80. This changed in the late 1960s with the introduction of directionally-solidified (DS) MAR-M200 + Hf airfoils. The DS process produces a <001> crystallographic orientation, which in superalloys exhibits excellent strain controlled fatigue resistance due to its low elastic modulus. The absence of transverse grain boundaries, a 60% reduction in longitudinal modulus compared with equiaxed grains, and its corresponding improved resistance to thermal fatigue and creep, permitted significant increases in allowable metal temperatures and blade stresses. Still further progress was achieved in the mid-1970s with the development of single crystal airfoils[1].

The first such material, PWA 1480, has a considerably simpler composition than preceding cast nickel blade alloys because, in the absence of grain boundaries, no grain boundary strengthening elements are required. Deleting these grain boundary strengtheners, which are also melting point depressants, increased the incipient melt temperature. This, in turn, allowed nearly complete γ' solutioning during heat treatment and thus a reduction in dendritic segregation. The absence of grain boundaries, the opportunity for full solution heat treatment, and the minimal post-heat treat dendritic segregation, result in significantly improved properties as compared with conventionally cast or directionally solidified alloys. Single crystal castings also share with DS alloys the <001> crystal orientation, along with the benefits of the resulting low modulus in the longitudinal direction.

Pratt & Whitney has developed numerous single crystal materials. Like most, PWA 1480 and PWA 1484 are γ' strengthened cast mono grain nickel superalloys based on the Ni-Cr-Al system. The bulk of the microstructure consists of approximately 60% by volume of cuboidal γ' precipitates in a γ matrix. The precipitate ranges from 0.35 to 0.5 microns and is an ordered Face Centered Cubic (FCC) nickel aluminide compound. The macrostructure of these materials

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[1] Gell, M., D. N. Duhl, and A. F. Giamei, 1980, "The Development of Single Crystal Superalloy Turbine Blades," *Superalloys* 1980, proceedings of the Fourth International Symposium on Superalloys, American Society for Metals, Metals Park, Ohio, pp. 205-214.

is characterized by parallel continuous primary dendrites spanning the casting without interruption in the direction of solidification. Secondary dendrite arms (perpendicular to solidification) define the interdendritic spacing. Solidification for both primary and secondary dendrite arms proceeds in <001> type crystallographic directions. Undissolved eutectic pools and associated microporosity reside throughout the interdendritic areas. These features act as microstuctural discontinuities, and often exert a controlling influence on the fatigue initiation behavior of the alloy. Also, since the eutectics are structurally dissimilar from the surrounding matrix their fracture characteristics will differ.

Single Crystal Fatigue

The fatigue process in single crystal airfoil materials is a remarkably complex and interesting process. In cast single crystal nickel alloys, two basic fracture modes, crystallographic and non-crystallographic, are seen in combination. They occur in varying proportions depending upon temperature and stress state. Crystallographic orientation with respect to applied load also affects the proportion of each and influences the specific crystallographic planes and slip directions involved. Mixed mode fracture is observed under monotonic as well as cyclic conditions.

Single crystal turbine blades are cast such that the radial axis of the component is essentially coincident with the <001> crystallographic direction which is the direction of solidification. Crystallographic fracture is usually seen as either octahedral along multiple (111) planes or under certain circumstances as (001) cleavage along cubic planes.

Non-crystallographic fracture is also observed. Low temperatures favor crystallographic fracture. At higher temperatures, in the 427C range, small amounts of non-crystallographic propagation have the appearance of transgranular fatigue in a related fine grain equiaxed alloy. Under some conditions, this propagation changes almost immediately to the highly crystallographic mode along (111) shear planes, frequently exhibiting prominent striations emanating from the fatigue origin and continuing to failure in overstress. Under other conditions the non-crystallographic behavior can continue until tensile failure occurs. At intermediate temperatures (around 760C) non-crystallographic propagation is more pronounced and may continue until tensile overload along (111) planes occurs, or may transition to subcritical crystallographic propagation. At 982C, propagation is almost entirely noncrystallographic, similar to transgranular propagation in a polycrystal.

Damage Catalogue

This program will identify and compile descriptions of the fracture morphologies observed in SC airfoil materials under various combinations of temperature and stress associated with advanced Navy aeropropulsion systems. We will suggest fatigue mechanisms for these morphologies and catalogue them as unique damage *states*. Most testing will be accomplished under ancillary funding, and therefore be available to this effort at not cost. The work is organized into four tasks, which are described in the following paragraphs.

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II. Program Organization

The program is structured into four tasks, three technical and one reporting. The individual tasks are outlined here.

Task 100 - Micromechanical Characterization

This task will define the mechanisms of damage accumulation for the various types of fracture observed in single crystal alloys. These fracture characteristics will be used to establish a series of Damage States which represent the fatigue damage process. The basis for this investigation will be detailed fractographic assessment of failed laboratory specimens generated in concurrent programs. Emphasis will be on specifically identifying the micromechanical damage mechanisms, relating them to a damage state, and determining the conditions required to transition to an alternate state.

Task 200 - Analytical Parameter Development

This task will extend current methods of fatigue and fracture mechanics analysis to account for microstructural complexities inherent in single crystal alloys. This will be accomplished through the development of flexible correlative parameters which can be used to evaluate the crack growth characteristics of a particular damage state. The proposed analyses will consider the finite element and the hybrid Surface-Integral and Finite Element (SAFE) methods to describe the micromechanics of crack propagation.

Task 300 - Probabilistic Modeling

This task will model the accumulation of fatigue damage in single crystal alloys as a Markov process. The probabilities of damage progressing between the damage states defined in Task 100 will be evaluated for input into the Markov model. The relationship between these transition probabilities and fatigue life will then be exploited to establish a model with comprehensive life predictive capabilities.

Task 400 - Reporting

Running concurrently with the analytical portions of the program, this task will inform the Navy Program Manager and Contracting Officer of the technical and fiscal status of the program through R&D status reports.

III. Technical Progress

During this reporting period we have reviewed our archival specimen fracture data base to further develop our micromechanical approach to IMQ (intrinsic material quality) defect incubation. We feel that the quantitative, qualitative and micromechanical characterization of these defects parallels (on the initiation side) our efforts to identify and categorize additional damage states (on the fracture side.)

In our previous report we discussed IMQ defects and reported the identification of the eutectic gamma-gamma prime phase as a temperature dependant IMQ defect.

Other defects that need to be assessed are the tantalum carbide (TaC) phase present in current chemistry PWA 1484 and microporosity found in non-hipped PWA 1484 and PWA 1480. To assess these defects from a quantitative standpoint, statistical frequency-of-occurrence distributions for size versus frequency of occurrence are needed.

A comprehensive evaluation of this type requires measurements from multiple heats of material and from components as well as test specimens, and is therefore beyond the scope of this program. It is possible however to obtain representative distributions of these IMQ defects for comparative purposes.

The distributions for microporosity in PWA 1480 and non hip PWA 1484 are shown in Figure 1. Since these observations were obtained from fatigue fracture surfaces at failure origins, the distributions provide an indication of the defect threshold size. PWA 1480 and PWA 1484 are plotted as a single population; An analysis of variance and F-test showed no statistically significant difference between the means and variances of the two populations when treated separately.

An increase in the carbon content of PWA 1484 to enhance its castability affected the TaC distribution. Insufficient fractures exist for the current chemistry PWA 1484 to provide a distribution based on fatigue crack initiation sites. In this case distributions are being developed via metallographic image analysis. The effort will also produce the distribution for the eutectic phase which has not been determined to date.

The threshold size for a TaC to initiate a fatigue crack has been estimated based on the minimum size origin present (Figure 2) in the available fracture data base. An attempt will be made to estimate this size for the eutectic phase in a similar manner. TaC defects fracture as opposed to decohesing (based on our current understanding) and recent study suggests that this may be a result of slip band impingment. This is associated with dislocation buildup at the defect/bulk microstructure interface. The determining factor affecting decohesion versus fracture should be studied.

The phenomena may be related to the relative defect morphologies. Qualitatively, the TaC is typically seen as a "Chinese Script" type carbide (Figure 3) while the eutectic phase (Figure 4) is comparatively spherical or ovoid in shape. The script shape would tend to be interlocked in the matrix while the eutectic phase is free to pull out cleanly without fracturing. The relative physical properties of the two phases would also favor fracture of TaC since the eutectic phase is considerably more ductile.

IV. Current Problems

No technical problems have been encountered during the reporting period.

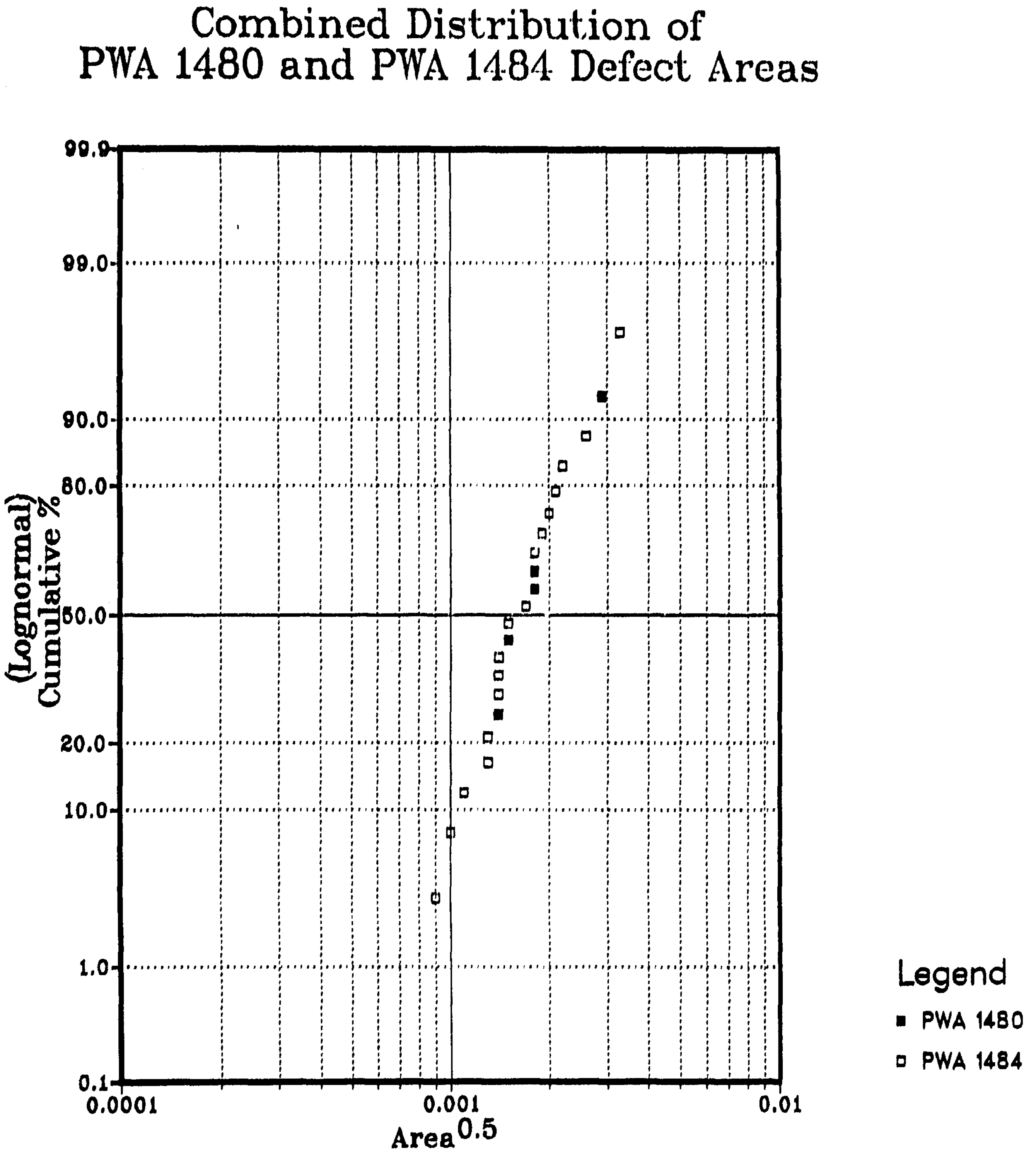

Figure 1. Size versus frequency of occurrence for microporosity in PWA 1480 and PWA 1484.

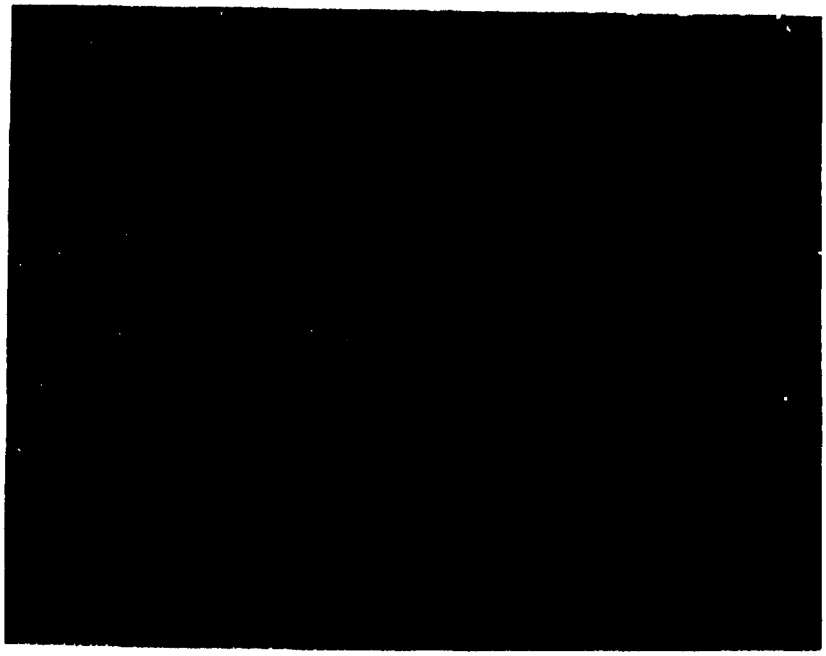

Figure 2: A secondary LCF initiation at a surface connected TaC approximately .00025" wide. (1000X)

Figure 3. A qualitative perspective on a TaC observed at a fatigue origin. This type of carbide morphology is commonly referred to as a "Chinese Script" carbide. **(500X)**

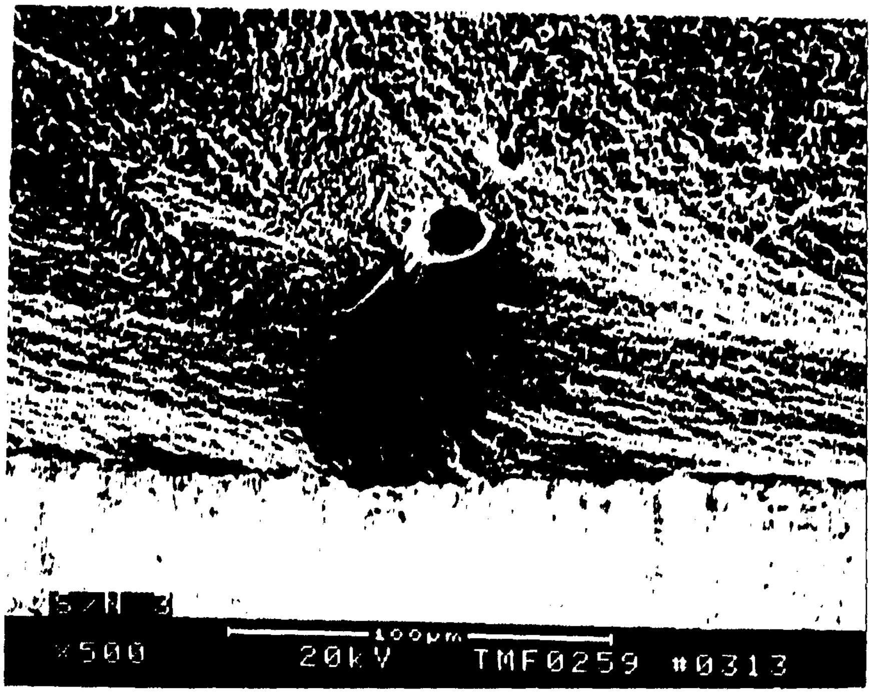

Figure 4. A fatigue origin showing the eutectic phase and a small micropore. The defect morphology is considerably different than that of TaC. **(500X)**

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